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Measurement of γ Angle Using $B \to DK$ at LHCb

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Measurements of the CKM angle γ via tree-level $b \to u$ and $b \to c$ interference are important for testing the Standard Model through the CKM unitarity constraint. In these proceedings, CP violation measurements with $B \to DK$ decays using 1 fb^{-1} of data collected in 2011 by LHCb are described, where 2-body ($\pi^+\pi^-$, K^+K^-, $K^+\pi^-$ and $K^-\pi^+$), 3-body ($K_s\pi^+\pi^-$ and $K_sK^+K^-$) and 4-body ($K^+\pi^-\pi^+\pi^-$ and $K^-\pi^+\pi^+\pi^-$) D^0 decays are considered. A combined measurement of γ using the above channels is also presented.

1 The LHCb Experiment

The LHCb apparatus [1] is an single-armed forward spectrometer covering the pseudo rapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV/c and 0.6% at 100 GeV/c which gives a mass resolution of 10$-$25 MeV/c^2 depending on decay modes. One of the crucial points for the measurement of γ through B to open charm decays is hadron identification. Two ring-imaging Cherenkov detectors are used to identify charged hadrons and they offer a 95% kaon identification efficiency with a 5% pion-to-kaon misidentification rate.

The LHCb trigger consists of a hardware trigger based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. The hardware trigger reduces the event rates from 40 MHz to 1 MHz which is further reduced to 5 kHz by the software trigger. It offers an efficiency around 20-50% for B decays with hadrons, depending on final states.

During the past two years of operation, the LHCb experiment collected 1.0 fb^{-1} of data at 7 TeV in 2011 and around 2 fb^{-1} at 8 TeV in 2012 with constant instantaneous luminosity during each bunch fill. The constant luminosity makes physics analysis less affected by pile-up effects. The results in this paper are obtained with the first 1 fb^{-1} of data.

2 The CKM Angle γ

The CKM angle γ, defined as $\gamma = \arg[-V_{ud}V^*_{ub}/(V_{cd}V^*_{cb})]$, is one of the least well-measured parameters of the CKM unitarity triangle defined through the relation $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$. A precise measurement of γ from tree-level interference is crucial to overconstrain the unitarity triangle while the comparison between γ at tree-level and γ at loop-level may shed light on new physics. As new physics is not expected to affect tree-level processes, γ at tree-level is theoretically clean and the relative precision $\delta\gamma/\gamma$ predicted by Standard Model is at $O(10^{-6})$. The γ angle can be accessed by different channels with interference between $b \to c$ and $b \to u$ transitions, it is thus important to combine measurements from different modes for better precision. It has been measured by various experiments [2,3]; the current combined precision is around $10 - 12^\circ$ [4,5]

Several methods to measure γ in tree decays using $B^- \to DK^-$ [a] are established, where D indicates a D^0 or $\bar{D}^0$ in this paper. There are three main methods according to different type of D decays:

1. : Gronau-London-Wyler (GLW) method [6]: γ is obtained through interference between $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$ where the D^0 or $\bar{D}^0$ decays to 2-body CP eigenstates, i.e. $D \to K^+K^-$, $D \to \pi^+\pi^-$ etc.

2. : Atwood-Dunietz-Soni (ADS) method [7]: γ is accessed through interference between the favoured $b \to c$ transition combined with the double-Cabbibo-suppressed $D^0 \to K^+\pi^-$ decay, and the suppressed $b \to u$ transition combined with the Cabbibo-favoured $\bar{D}^0 \to K^+\pi^-$ decay.

3. : Giri-Grossman-Soffer-Zupan (GGSZ) method [8]:γ is obtained through interference between $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$ where the D^0 or $\bar{D}^0$ meson decays to self-conjugated multi-body final states, i.e. $D \to K_s\pi^+\pi^-$, $D \to K_sK^+K^-$ etc.

The decay rate can be generally written as:

$$\Gamma(B^\pm \to D[\to f]K^\pm) = A_c^2(r_D^2 + (r_B^K)^2 + 2r_B^K r_D \mathrm{Re}(e^{i(\delta_B^K + \delta_D \pm \gamma)})), \tag{1}$$

where δ_B^K, δ_D are strong phase difference for B and D decays with different transition; r_B is the amplitude ratio between $b \to u$ and $b \to c$ transitions; r_D is the ratio of D decay amplitudes; A_c is the normalisation factor which can be cancelled out. r_B^K is around 0.1 for $B \to DK$ which gives better sensitivity on γ than $B \to D\pi$ decays ($r_B^\pi \sim 0.01$) [9]. Time-integrated CP violation using the above three methods with $B \to DK$ are measured by LHCb and discussed in the following section.

3 γ studies with $B \to DK$ at LHCb

3.1 Two-body D Decays

The following two-body D decay channels are studied: $D \to K^+K^-$, $D \to \pi^+\pi^-$, $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$ with which a combined GLW and ADS analysis is performed [10]. The observables, for the GLW mode, are $R_{CP+} = 2\frac{\Gamma(B^-\to D_{CP+}K^-)+\Gamma(B^+\to D_{CP+}K^+)}{\Gamma(B^-\to D^0K^-)+\Gamma(B^+\to \bar{D}^0K^+)}$ and $A_{CP+} = \frac{\Gamma(B^-\to D_{CP+}K^-)-\Gamma(B^+\to D_{CP+}K^+)}{\Gamma(B^-\to D^0K^-)+\Gamma(B^+\to \bar{D}^0K^+)}$, which depend on γ by $R_{CP+} = 1 + (r_B^K)^2 + 2r_B^K \cos\delta_B^K \cos\gamma$ and $A_{CP+} = \frac{2r_B^K \sin\delta_B^K \sin\gamma}{R_{CP+}}$. Similar variables and their relationship with $r_B^K, \delta_B^K, \gamma$ can be defined and deduced for the ADS mode [7].

[a] Charge-conjugation is implied throughout this paper unless otherwise stated.

The above defined variables are calculated using signal yields in B^- and B^+ decays, where most of efficiency effects cancel out except those from detection asymmetry and production asymmetry which are obtained from control samples. We obtain the following results:

$$\begin{aligned} R_{CP+} &= 1.007 \pm 0.038 \pm 0.012, \\ A_{CP+} &= 0.145 \pm 0.032 \pm 0.010 \end{aligned}$$

for the GLW method, averaged over $D \to K^+K^-$ and $D \to \pi^+\pi^-$, which corresponds to a CP violation of 4.5σ significance and

$$\begin{aligned} R_{ADS}(K) &= 0.0152 \pm 0.0020 \pm 0.0004, \\ A_{ADS}(K) &= -0.52 \pm 0.15 \pm 0.02 \end{aligned}$$

for the $B \to DK$ ADS method, which corresponds to a 4.0σ significance CP violation. The first uncertainty of the result is statistical and the second one is the systematic uncertainty. Combining the two methods, we have the first observation of direct CP violation at 5.8σ significance in the 2-body D decays of $B \to DK$.

3.2 Three-body D Decays

A model independent method is applied for the GGSZ mode with $D \to K_s\pi^+\pi^-$ and $D \to K_sK^+K^-$ [11] using inputs from CLEO measurements [12]. The Dalitz plots are divided into different bins (16 for $D \to K_s\pi^+\pi^-$ and 4 for $D \to K_sK^+K^-$) according to the distributions obtained from Dalitz analysis. It should be noted that the analysis is independent from Dalitz modelling, any deviation from reality only reduces the sensitivity to γ but does not introduce bias. The number of events in each bin is given by

$$\begin{aligned} N^+_{\pm i} &= h_{B^+}[K_{\mp i} + (x_+^2 + y_+^2)K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_+ c_{\pm i} \mp y_+ s_{\pm i})], && (2) \\ N^-_{\pm i} &= h_{B^-}[K_{\pm i} + (x_-^2 + y_-^2)K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_- c_{\pm i} \pm y_- s_{\pm i})], && (3) \end{aligned}$$

where $h_{B^\pm}$ is the normalisation factor for $B^\pm$, K_i represent the Dalitz distribution in flavour-tagged D decays; c_i and s_i are inputs from CLEO measurements. $x_\pm = \mathrm{Re}[r_B^K e^{i(\delta_B^K \pm \gamma)}]$ and $y_\pm = \mathrm{Im}[r_B^K e^{i(\delta_B^K \pm \gamma)}]$ are the quantities to be measured. In total, we have around 660 signals in the $K_s\pi^+\pi^-$ mode and 100 signals in the $K_sK^+K^-$ mode. The best fitted value for $x_\pm$ and $y_\pm$ are:

$$\begin{aligned} x_- &= (0.0 \pm 4.3 \pm 1.5 \pm 0.6) \times 10^{-2}, \\ y_- &= (2.7 \pm 5.2 \pm 0.8 \pm 2.3) \times 10^{-2}, \\ x_+ &= (-10.3 \pm 4.5 \pm 1.8 \pm 1.4) \times 10^{-2}, \\ y_+ &= (-0.9 \pm 3.7 \pm 0.8 \pm 3.0) \times 10^{-2}, \end{aligned}$$

where the first error is the statistical uncertainty, the second one is the systematic uncertainty and the third one is the uncertainty from CLEO inputs. Using the above value, we can extra γ from the GGSZ mode only, which give a value of $(44^{+43}_{-38})^\circ$.

3.3 Four-body D Decays

There are also measurements using 4-body decays $D^0 \to K^-\pi^+\pi^-\pi^+$ and $D^0 \to K^+\pi^-\pi^+\pi^-$ [13]. An analysis similar to 2-body ADS analysis is performed. There are around 40 signals observed for the ADS $B \to DK$ mode which corresponds to 5.7σ observation and around 160 signals for the ADS $B \to D\pi$ mode which corresponds to more than 10σ observation. The measured value for $R^{K3\pi}_{ADS}(K)$ and $A^{K3\pi}_{ADS}(K)$ are 0.0124 ± 0.0027 and -0.42 ± 0.22 respectively. This is then used to give constraint on r_B^K which yields $r_B^K = 0.097 \pm 0.011$.

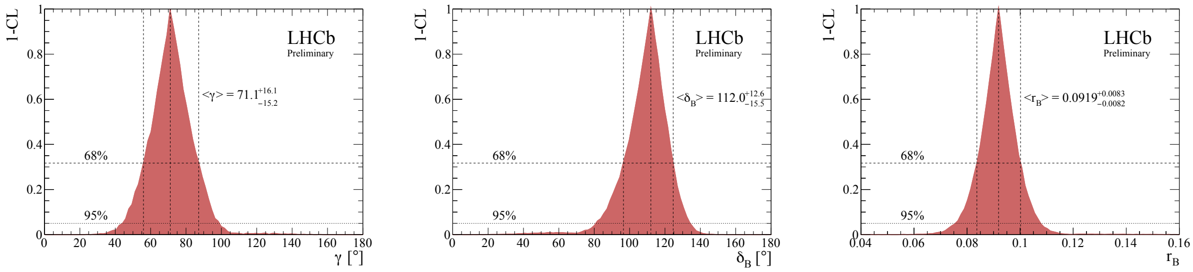

Figure 1: 1 - CL curves for γ (left), δ_B (centre) and r_B^K (right) from the combination of the measurements using $B \to DK$ decays.

3.4 γ Combination

Using the above measurements, the recent evidence for a difference in the CP asymmetries in $D \to K^+K^-$ and $D \to \pi^+\pi^-$, $\Delta a_{CP}^{dir} = (-0.656 \pm 0.154) \times 10^{-2}$ [14] and the CLEO inputs [15], a combination is made to extra γ [16]. A frequentist technique is used with D mixing effect ignored at this level. The confidence level (CL) curves of γ, δ_B and r_B^K are shown in Fig. 1. The most probable value of γ is 71.1 with 68% CL interval $[55.4, 87.7]^\circ$ and 95% CL interval $[41.4, 101.3]^\circ$. The fitted value for r_B^K and δ_B^K are 0.092 ± 0.008 and $(112.0^{+12.6}_{-15.5})^\circ$. The results are in agreement with the combined results measured by Babar [2] and Belle [3] with similar precision.

4 Conclusion

In this paper, the results of $B \to DK$ measurement at the LHCb experiment using 1 fb^{-1} of data are described. A combination is made which gives $\gamma = 71.1^\circ$ with an uncertainty around 16°; it is in agreement with the combined results published by other experiments.

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